The Mars Laser Communication Demonstration*

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Abstract—This paper provides the status of the Mars Laser Communication Demonstration Project, a joint project between NASA's Goddard Space Flight Center (GSFC), the California Institute of Technology Jet Propulsion Laboratory (JPL), and the Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL). It reviews the current ideas/designs for the flight and ground segments, the critical technologies required, and the concept of operations. The laser communication (lasercom) flight terminal will be flown on the Mars Telecom Orbiter (MTO) to be launched by NASA in 2009, and will demonstrate a technology which has the potential of vastly improving NASA's ability to communicate throughout the solar system.

1. INTRODUCTION

In the near future the National Aeronautics and Space Administration anticipates a significant increase in demand for long-haul communications services from deep space to Earth. Distances will range from 0.1 to beyond 40 AU[1], with data rate requirements in the 1's to 1000's of Mbits/second. The near term demand is driven by NASA's Space Science Enterprise which wishes to deploy more capable instruments onboard spacecraft and increase the number of deep space missions. The long term demand is driven by missions with extreme communications challenges such as very high data rates from the outer planets, supporting sub-surface exploration, or supporting NASA's Human Exploration and Development of Space Enterprise beyond Earth orbit.

NASA's Goddard Space Flight Center, the Jet Propulsion Laboratory, and MIT's Lincoln Laboratory are working together to demonstrate optical communications on the 2009 Mars Telecom Orbiter (MTO). The Mars Laser Communications Demonstration (MLCD) Project will demonstrate one possible solution in meeting NASA's future long-haul communication needs. Lasercom sends information using beams of light and optical elements, such as telescopes and optical amplifiers, rather than RF signals, amplifiers, and antennas. Near-Earth lasercom systems have been demonstrated (GeoLITE[1] in the US, GOLD[2] in the U.S. and Japan, and SILEX in Europe[3]), and the technology has the potential to revolutionize deep space communications.

NASA has sponsored research and development in deep space lasercom for many years[4]. In 2002 and 2003, NASA sponsored the Mars Lasercom Study at MIT/LL to develop the demonstration concept and some strawman designs. The demonstration Mars terminal is being designed to provide a continuous data link of between 1 and 100 Mbits/second from Mars to Earth, depending on the instantaneous distance and atmospheric conditions. The 100 Mbits/second data rate will be a significant performance increase over today's RF systems. The project is planning to use ground terminals capable of receiving the encoded laser beam and transmitting an uplink beacon laser to the flight terminal, for active tracking and pointing control of the narrow laser beam. Critical technologies for receiving the deep space signal include low-cost large collection apertures and low-noise photon-counting detectors.

Lasercom will enable bandwidth-hungry instruments, such as hyper-spectral imagers, synthetic aperture radar (SAR) and instruments with high definition in spectral, spatial or temporal modes to be used in deep space exploration. The Mars Laser Communications Demonstration Project will provide much needed engineering insight by the end of this decade.

[1] Approximately 150 million km

2. Overview of Deep Space Laser Communications

Several organizations in the United States, Europe, and Japan are working on multi-Gbits/second lasercom systems for near Earth applications[5]. Unfortunately, the technology suitable for near Earth does not easily extend to deep space requirements. To get a sense of the difficulty involved, consider that a geostationary orbit is approximately 36,000 km above Earth while at its farthest distance Mars is approximately 380,000,000 km away, i.e., approximately 10,000 times farther. Since the power density changes as the square of the distance, this means that there is a factor of approximately 100,000,000 or 80 dB additional space loss when compared to GEO links. Simply transporting a 10 Gbits/second lasercom system designed for near Earth applications from Earth to Mars would result in only 100 bits/second. An improvement of 40-60 dB is required to provide 1-100 Mbits/second from Mars.

Doing a few simple things like increasing the transmit aperture and laser power can provide a few dBs. A significant number of the required dBs can be obtained by increasing the receive aperture size from 10's of centimeters to between 5 and 10 meters. This is analogous to what is done by today's RF based Deep Space Network. The last dBs will have to come through the use of more efficient signaling, detection architectures, and high performance error-correcting codes that operate 0.5 - 0.75 dB from theoretical channel capacity.

The fiber telecommunications industry uses optical pre-amplified receivers with simple modulation formats such as on-off keying (OOK). They have also used pre-amplified Differential Phase Shift Keying (DPSK) for very high-speed free space links. Although fairly efficient, especially with near capacity achieving forward error correction (FEC) coding, neither of these formats achieves anywhere near the ultimate efficiency of coded optical communication. They are used, though, because as of today, they are the best techniques for achieving the high gain-bandwidth performance required in efficient receivers at multi-Gbits/second rates. High-order alphabet size modulations, such as low duty-cycle pulsed formats, are known to provide high efficiency at the cost of considerable bandwidth expansion. For the deep space optical channel, this extra bandwidth is well within technological limits, and low-noise photon-counting reception is the most efficient means known to date for receiving it. Photon-counting detectors have been developed that detect photons with a time resolution set by an external clock.

A major area of concern for deep space lasercom is the need to work very close to the Sun. This is easily seen when considering the outer planets (e.g. from Pluto, the Earth is always very close to the Sun), but is also very important for a system at Mars. Figure 1 illustrates what is happening during solar conjunction. SEP is the Sun-Earth-Probe angle while SPE is the Sun-Probe-Earth angle. Small SEP angles interfere with the Earth terminal's ability to acquire and track the lasercom signal. Small SPE angles interfere with the Mars terminal's ability to acquire and track the uplink beacon laser from Earth. During solar opposition, small SPE angles also affect the Mars terminal as the Earth is again very close to the Sun.

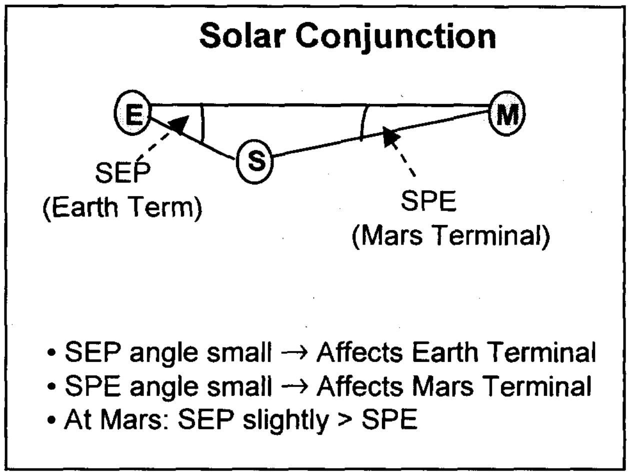

Figure 1 – The Effect of Solar Conjunction

Each day there is a time of sunrise, Mars rise, sunset, and Mars set. Most of the time, both the Sun and Mars will be in the sky simultaneously. From a lasercom systems engineering perspective, a critical design driver is the fact that Mars is simultaneously at its farthest distance and at its smallest SEP angle. The communication outages that arise when either the Earth or Mars is too close to the Sun have been evaluated for various SPE angles (and the corresponding SEP angles during solar conjunction) and are shown in Table 1.

Table 1. Annual Communication Outages in Days vs. SPE Angles

SPE Angle (Degrees)	SEP Angle (Degrees)	Outage (Days)
2	2.8	23
4	5.7	49
6	8.6	75
8	11.4	100
10	14.3	126
15	21.9	190
20	28	255

3. Modulation and Coding

A key aspect in designing a Mars-Earth communications link with the highest power-efficiency is an effective modulation format with error-correction coding. The low-duty cycle modulation format selected for the Mars terminal is

Pulse Position Modulation (PPM). In the PPM modulation format, exactly one out of M pulses is on, thus delivering $\log_2(M)$ bits for every pulse, as shown in Figure 2.

The modulator is paired with a Forward Error Correction (FEC) encoder designed specifically to match the PPM channel. The most common FEC code paired with PPM has long been Reed-Solomon (RS) codes since they both deal in blocks of log2(M) bits. One advantage of RS codes is that off-the-shelf chipsets exist for coder/decoders. But, one disadvantage is that RS codes do not achieve capacity, even with a more complex soft-decision decoder. Another possibility is to use a Turbo-Code using iterative decoding which comes within 1 dB or so of capacity. Codes are typically constructed by two or more constituent part, separated by long interleavers, which implicitly create very long codewords. The decoder finds a constituent code outputting values akin to maximum likelihood information (called "extrinsic information"). This information is then de-interleaved and applied to the decoder for the other constituent part. The process is iterated 5-10 times and the resultant output bits are very nearly the maximum likelihood (ML) decoded values for the very long codewords, even though the true ML calculation would have been extremely difficult.

We can achieve within ~1 dB of capacity using a pulsed modulation with a photon counting receiver. Operating curves are shown in Figure 3 for various alphabet size M with 0.17 noise photons per slot. For example, with 64-ary modulation, trying to achieve 10 Mb/s (or 0.01 bits per slot with a 1 ns pulse) requires about –21 dB photons per ns slot.

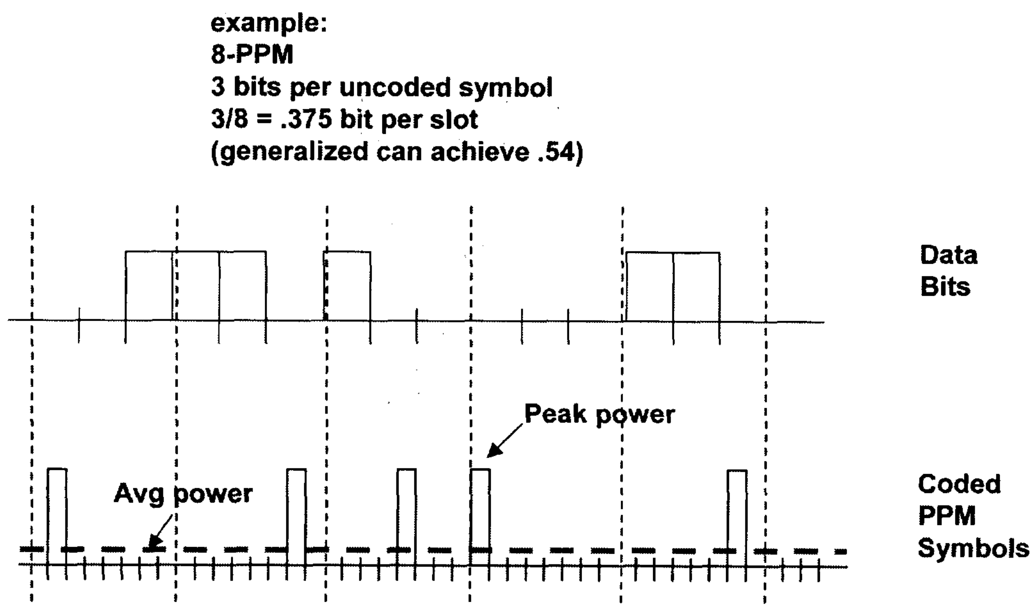

Figure 2 - PPM Modulation Format Example

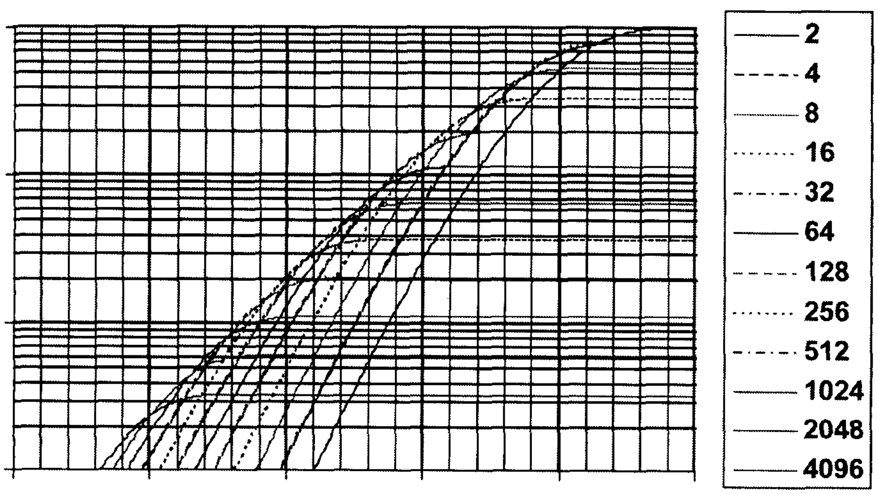

Figure 3 - PPM Photon Counting Operating Curves for Number of Slots M=2 to 4096 and 0.17 Noise Counts Per Slot.

4. THE MLCD FLIGHT TERMINAL

The primary functions of the MLCD flight terminal (FT) on the downlink are: to efficiently generate optical power that can have data modulated onto it; transmit this optical power through efficient optics; and aim the very narrow beam at earth, despite platform vibrations, motions, and distortions. On the uplink, the FT must track a beacon from Earth that will be used to facilitate pointing and receive commands .

Flight Terminal Configuration

The Mars lasercom terminal utilizes a 30.5 cm aperture 15X on-axis telescope. The 1 mrad field of view required to accommodate the spacecraft pointing errors is readily accommodated without significant wavefront quality degradation.

A solar window is included to reject at least 80% of the solar load while passing more than 90% of the beacon and communications wavelengths. This greatly reduces the thermal loads on the telescope mirrors and metering structure and reduces the size of the thermal radiator. A shutter is provided to block the beam path at those times when the sun is directly on-axis to prevent damage to the tracking and transmitting optics.

A small portion of the transmit beam will be directed onto the Slow Beacon Camera and Transmit Monitor (CCD) by means of a retroreflector to allow continuous monitoring of the transmitter beam pointing. Since the CCD can not distinguish between the two beams during boresighting, a shutter is provided to block the transmit beam as required.

A Point Ahead Mirror (PAM) is provided to allow the beacon and transmit beam paths to be offset by the appropriate point ahead angle.

A block diagram of the FT is shown as Figure 4.

Pointing And Stabilization System

Figure 5 shows a block-diagram of the pointing control hardware for an inertial reference aided beacon-tracking terminal. The major components are:

- Magnetohydrodynamic Inertial Reference Unit (MIRU)
- Fast steering mirror (FSM)
- Fast readout quad-cell
- Slow beacon camera and transmit monitor
- Point-ahead mirror (PAM)

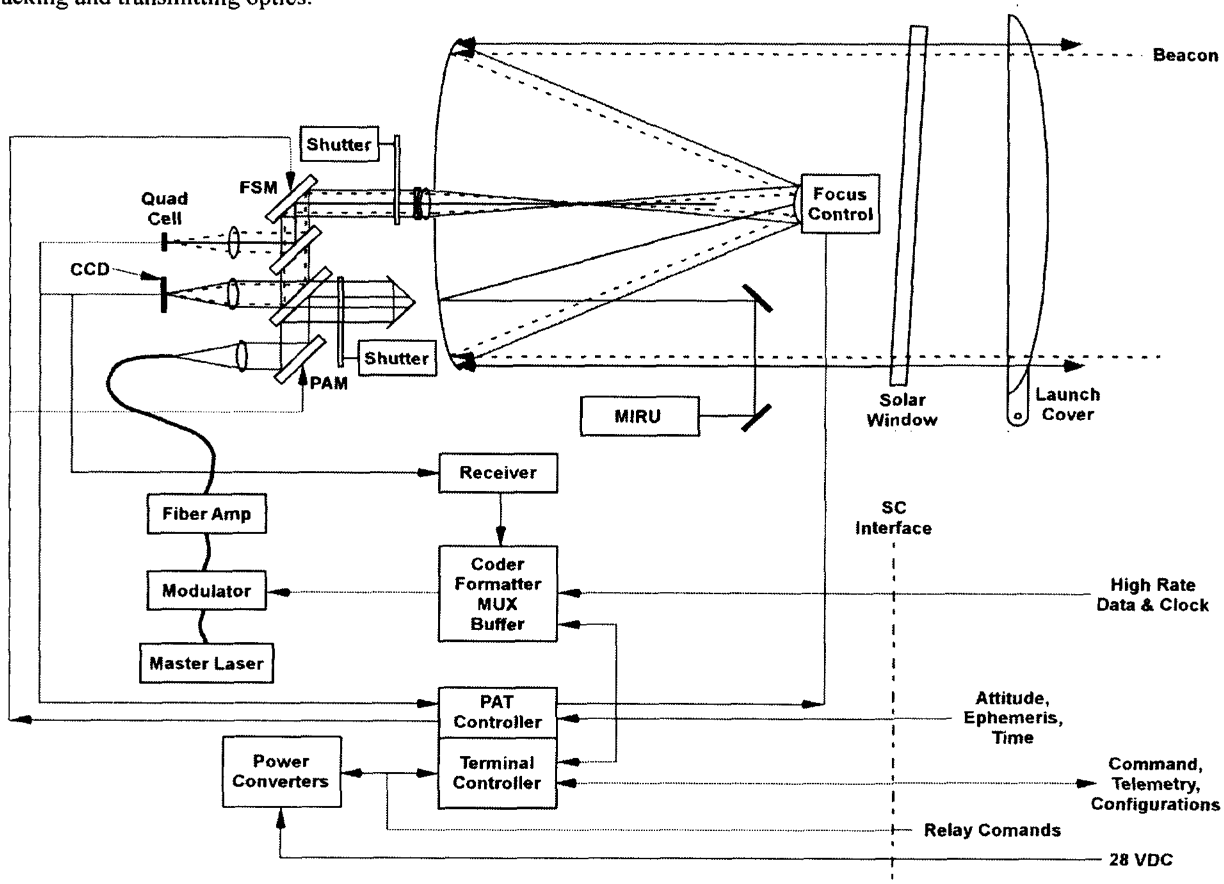

Figure 4 - FT Configuration Block Diagram

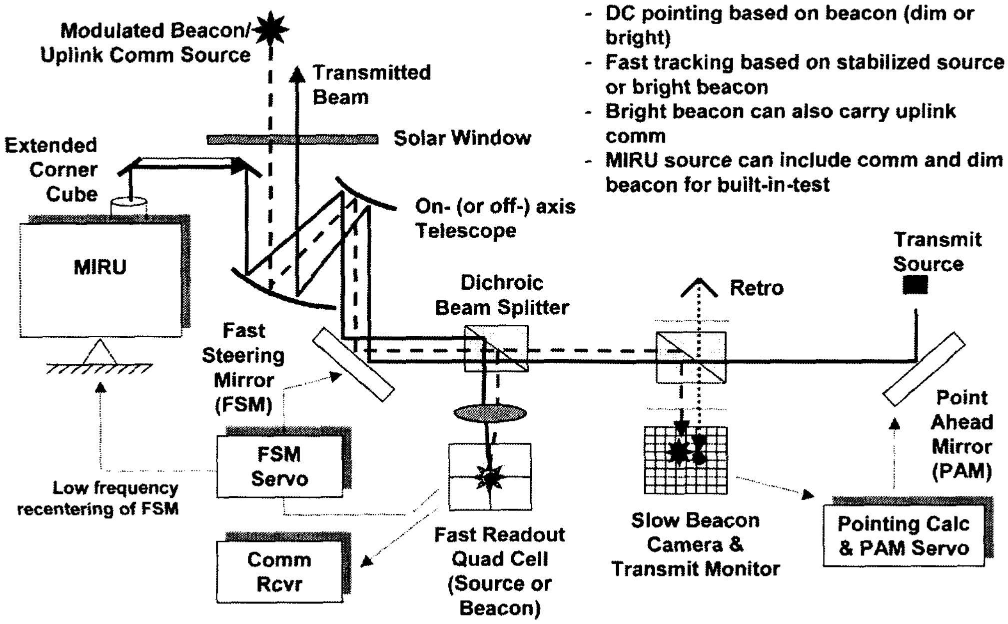

Figure 5 - MIRU-Aided Beacon Tracking Diagram

The MIRU is an inertially stabilized platform for a collimated laser source. It is currently being developed by Applied Technology Associates of Albuquerque, NM under a Phase II SBIR for NASA. It is a functionally similar to the Inertial Pseudo-Star Reference Unit (IPSRU) developed by Draper Laboratory for the Air Force Phillips Laboratory's High Altitude Balloon Experiment[6]. It consists of a combination of magnetohydrodynamic inertial sensors, voice-coil actuators, proximity sensors, and a precision gyroscope. The quiescient jitter of the stabilized platform is expected to be less than 100 nrad. An extended corner cube folds the collimated laser light into the lasercom telescope.The fast steering mirror is used to steer the incoming and outgoing beams within the telescope field of regard, and to stabilize the beams in order to reject spacecraft-borne motions.

The fast readout quad-cell is designed to detect modulated optical power and allow for closed-loop tracking of a modulated source via the FSM control loop servo. The fast readout quad cell can either detect a modulated local source on the MIRU stabilized platform (to stabilize the telescope relative to the local "pseudo-star"), or, if sufficient power is available, the fast readout quad-cell can directly sense the modulated uplink beacon and allow the FSM servo to track the uplink beacon. In general, the beacon uplink power may not be sufficient for high-bandwidth tracking, so the stabilized source on the MIRU provides a stable reference to allow closed loop tracking and rejection of spacecraft motions.

The slow beacon camera and transmit monitor provides two primary functions: it allows tracking of a dim beacon signal in order to correct for MIRU bias and drift; and it allows for tracking of the transmitter source in order to correctly align the receive and transmit beams. Orientation of the transmit beam about the line-of-sight is based on the spacecraft attitude determination and control system.

The point-ahead mirror is required when operating in direct beacon tracking mode (a mode to be demonstrated depending on available beacon power and atmospheric conditions). Since the fast steering mirror centers the tracked uplink beacon on the quad cell during this mode, an extra degree of freedom is needed to apply the point ahead angle to the transmit beam. Note that the point-ahead mirror is not required when using the MIRU for aided tracking and stabilization – the MIRU can provide the extra degree of freedom to offset the transmit and the receive beams.

During MIRU-aided pointing, the MIRU points a locally stabilized collimated source, nominally along the telescope boresight, but it can be offset by +- 2.5 mRad to cover a large field of regard. When the FSM servo loop tracks this low-jitter source, the received light at the slow beacon camera and transmit monitor will be stabilized to the jitter level of the MIRU plus the jitter due to the FSM servo tracking performance. Thus, the light at the slow beacon camera and transmit monitor will be low-jitter, and the camera data may be used to detect a slow, weak uplink beacon (nominally 1 Hz tracking bandwidth). The position of the transmit beam relative to the receive beacon defines the point ahead angle, and is directly detected from the slow beacon camera and transmit monitor data. The MIRU pointing bias is then modified until the point-ahead angle (sensed at the slow beacon camera and transmit monitor) is the desired value. The desired point-ahead angle is calculated off-line based on the orbital geometry of the Mars and Earth terminals.

Transmitter

The Master Oscillator Power Amplifier (MOPA) transmitter architecture is modular, allowing for a more flexible choice of waveforms and independent design and optimization of the laser, modulator, and power amplifier. The design is commonly used for high rate optical communications in the telecom industry at Mbit/second rates to 10's of Gbit/second and beyond with near quantum-limited performance [7,8,9]. The MOPA transmitter architecture selected for the strawman design is shown in Figure 6.

The master laser selected for the strawman design is a commercially available fiber distributed feedback (DFB) laser, which consists of a DFB fiber Bragg grating (FBG) written into Ytterbium doped fiber, pumped by a 980nm laser diode. Both the pump laser and FBG are mature technologies, used throughout the telecom industry.

The modulator selected is a $LiNO_3$ Mach-Zehnder modulator (MZM), a technology that is also used throughout the telecom industry (at 1.5μm) for high rate, high performance communications. Commercially available MZMs were evaluated and the following parameters were observed: Insertion Loss < 3 dB; 3 dB Bandwidth > 10 GHz; $V\pi$ (@ 1 GHz) ~ 2 volts; ER @ 1 GHz ~ 20 dB. A cascade of two MZMs in series is used to provide ~40 dB extinction ratio which is sufficient for generating large constellation M-PPM waveforms without penalty.

High power Ytterbium doped fiber amplifiers (YDFAs) are commercially available from several vendors with ~15% wall-plug efficiency. In the strawman design a filtered and isolated high gain preamplifier precedes the power amplifier, providing sufficient power to saturate the subsequent power amp and efficiently extract the 5W average output.

Mechanical Configuration

The Mars terminal consists of separate optical and electronic modules mounted to the Mars Telecom Orbiter (MTO). The MTO will maintain Earth pointing to within ±1 mrad, limiting the maximum Sun angles to 40°off the spacecraft pointing direction. The configuration of the Mars terminal is shown as Figure 7.

The Mars terminal will include a passive vibration isolation system. Lower resonant frequency systems provide better isolation of high frequency disturbances but require longer stroke struts than a higher frequency system. Low frequency isolation systems are more prone to interacting with the launch vehicle avionics during launch and so may need to be caged during launch. The proposed 20 Hz isolation system is a good compromise between the three constraints of stroke, isolation, and launch vehicle interactions. Such a system should not need to be caged during launch, particularly if it is a highly damped system. In this way, the isolation system also protects the optical components during launch.The telescope consists of an Invar metering structure with Ultra Low Expansion (ULE) glass mirrors. The telescope is athermalized by having the baseplate made of aluminum. If the telescope warms up the metering structure would get slightly longer, tending to defocus the telescope. However, as the baseplate also warms up, the splay of the Invar metering truss increases which tends to foreshorten the structure. The geometry of the metering structure was selected to balance these two effects.

Protective covers fabricated from molded carbon fiber material will be included to support the Multi-Layered Insulation (MLI) that will cover the telescope and the small optics on the rear of the telescope baseplate.

The electronics module is mounted to a thermal radiator that is thermally isolated from the spacecraft. This radiator will have heaters to maintain a minimum survival temperature of -30°C and would be sized to limit the peak operating temperature to 50°C during times of peak power dissipation.

The telescope assembly includes a cover to protect the solar window up until the first use after launch. It also includes a thermal radiator to dissipate the solar load and internal dissipation from the LBM, FSM, MIRU, and tracking detectors.

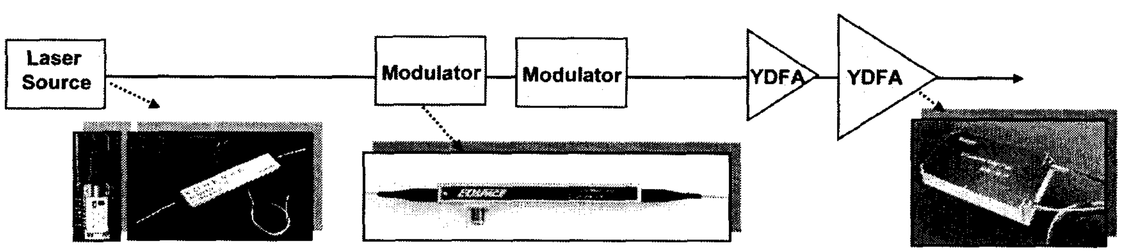

Figure 6 - MOPA Transmitter Architecture

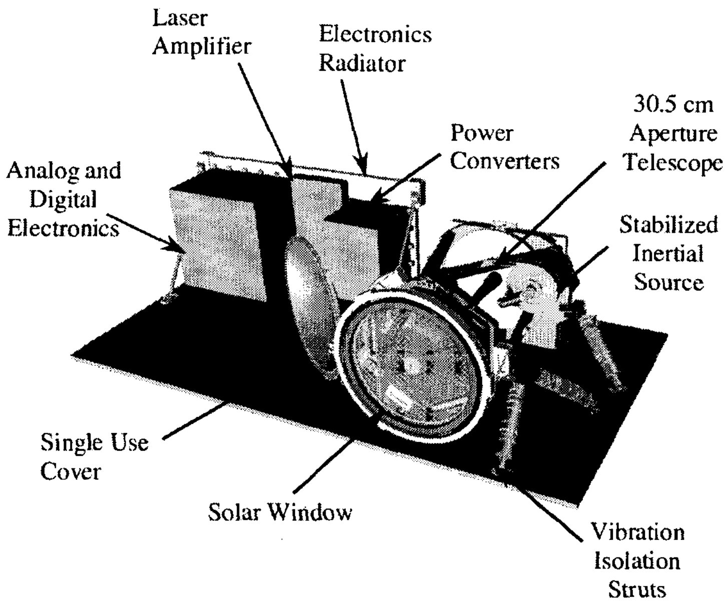

Figure 7 - Flight Terminal Configuration

The rear end of the telescope assembly supports a small optical bench, shown in Figure 8, which contains the tracking, transmitting, and boresighting optics

The Fast Steering Mirror (FSM) is located at the telescope's exit pupil to minimize beam walk as the FSM corrects for spacecraft pointing errors. Both the FSM and the Point Ahead Mechanism (PAM) are based on commercially available mechanisms. The transmitter collimator is fed with a single-mode optical fiber with the laser located in the electronics module. The quadrant detector assembly includes preamplifiers to boost the signal level prior to sending the signals to the electronics module.

A shutter assembly is included to block solar illumination of the CCD detector, quadrant detector, and transmit fiber for those times when the sun is very close to being directly on-axis.

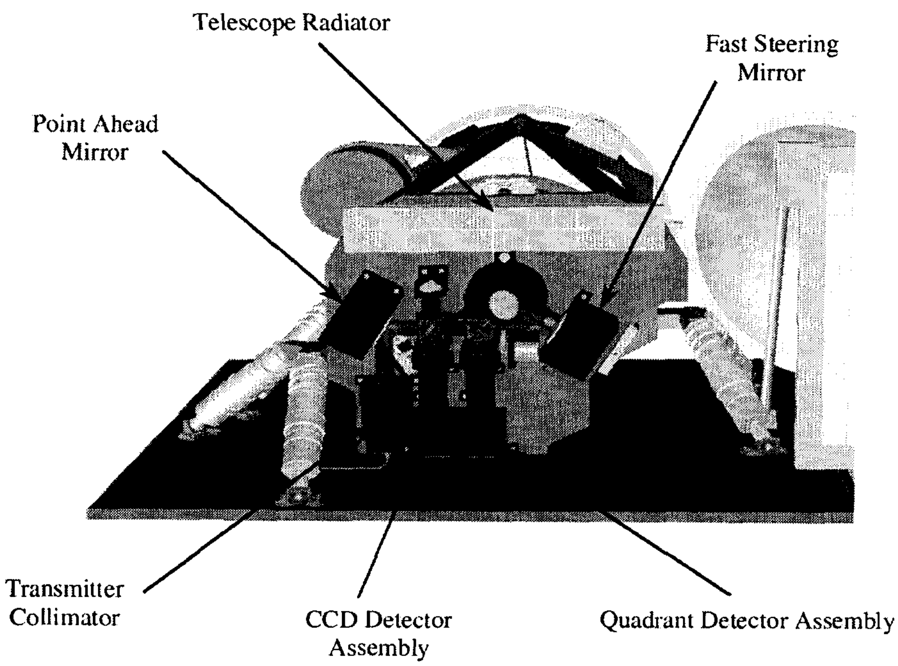

Figure 8 - Small Optics Assembly

5. THE EARTH TERMINALS

In the RF world, there is the Deep Space Network (DSN) to receive the RF signals from MTO. In the case of the MLCD, there is no existing "Optical DSN" and hence we need to provide our own Earth terminal. The Earth terminal must provide two functions; an Earth Receive Terminal (ERT) to receive the communications signal from Mars and an Earth Transmit Terminal (ETT) to transmit an uplink beacon so that the FT points to the correct location on the Earth and to send commands to the FT.

Earth Receive Terminal (ERT)

Two approaches are being considered for providing Earth terminal functionality. The first approach is to use existing astronomical telescope facilities to try to minimize the need for "infrastructure" development. The second approach is to build new ERTs (and ETTs) specifically designed for this application.

Use of Existing Astronomical Telescopes

Figure 9 shows the block diagram of how we could interface to an existing telescope.

The project is investigating the use of retrofitted astronomical telescopes as temporary signal receivers. One of the prime candidates for this is the venerable 5-meter (200-inch) Hale Telescope on Palomar Mountain (Figure 10). Its large aperture, mature infrastructure and relative accessibility make it a good choice for this demonstration. It is predicted to achieve data rates of a few dozen Mbits/second during Mars opposition, while supporting data rates of several Mbits/second during the majority of the remaining Martian year.

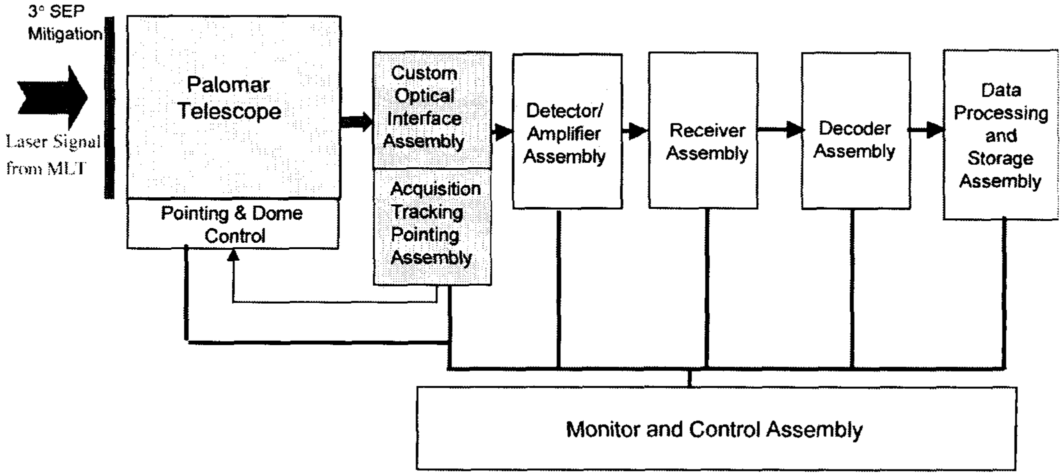

Figure 9 - Using An Existing Telescope

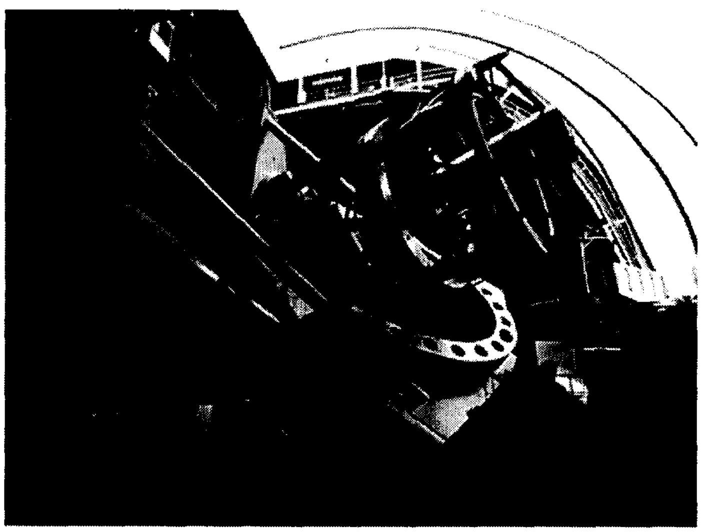

Figure 10 - The 5-Meter Hale Telescope on Palomar Mountain

The main drawback to the use of existing astronomical telescopes as data receivers is their limited ability to operate during daylight hours, especially at angles less than 10 degrees from the sun. Strategies for achieving this goal are being considered, including the use of highly reflective spectral filters, and large external reflecting flats. The challenges (and costs) of executing one of these strategies, while not necessarily benign, are expected to be significantly less troubling than the development of new facilities and support infrastructure.

Detectors for Large Apertures—Photon-counting detectors for single large aperture telescopes are required for the near capacity performance mentioned earlier. In order to match the atmospheric "seeing" degraded focal spot sizes these detectors must have a large area (nominally, 1-2 mm diameter). They must simultaneously have fast (~ 1-2 ns) rise times for resolving the time of arrival of laser pulses. The photon-detection efficiency (PDE) i.e. the fraction of incident photons detected must also be high (40-50% @ 1064 nm). The latter ensures the ability to communicate within spacecraft power constraints. Finally, the detector must possess sufficient internal gain to overcome additive noise from post-detection electronics.

High PDE requirements combined with need for internal gain, narrow detector selection to avalanche photo-diodes (APD), which can count single photons. APD's operate with bias levels above breakdown, in the so-called Geiger mode [10] (elaborated below), and at bias levels less than that required for inducing breakdown. The Geiger mode "dead" time of the order of 0.1 – 1 μs limits laser pulse repetition frequencies that can be supported. Moreover, background photons and occasional dark events will further limit the signal photon update rate. The single sub-geiger mode APD, on the other hand, can be operated without "dead" time but with noise from gain variance and signal conditioning electronics. The latter can be greatly reduced by using cryo-cooled low noise amplifiers. The former can be improved by careful device selection. Efforts are underway to develop a near infra-red (1-1.064 μm) sub-geiger mode photon counting APD assembly that provides the sensitivity, bandwidth and photo-detection efficiencies demanded by the photon starved deep space optical links. Figure 11 shows a representative APD detector and low noise amplifier used in the assembly. APD theory suggests that approaching within 3-4 dB the capacity curves of Figure 4 should be possible. The extent to which the noise inherent in using APD sub-geiger photon-counting can be minimized will determine the ultimate performance.

Using photon-counting arrays in the focal plane of a single large telescope is also a viable option. The advantage of implementing arrays is that per pixel noise and bandwidth can be improved. Adaptive algorithms [11] for array readout can also improve the signal to noise when operating in the presence of high background. Arrays also open up the possibility of taking advantage of the near ideal photon counting Geiger mode arrays, provided a sufficiently large array can be obtained in order to minimize the signal blockage due to the "dead" time constraint. These options are currently being evaluated

The optical receiver backend following optical detection will utilize digital signal processing to implement synchronization, demodulation and decoding functions.

Two possibilities are being considered for new apertures. One is the development of large single aperture "photon buckets. The second is the use of arrays of small telescopes.

New Large Single-Aperture ERT

Development of a 5-meter to 10-meter class optical receiver has been considered in relative detail [12]. Though these receivers are occasionally compared with expensive equivalent-aperture telescope facilities, there are important differences which allow for significantly lower costs. The

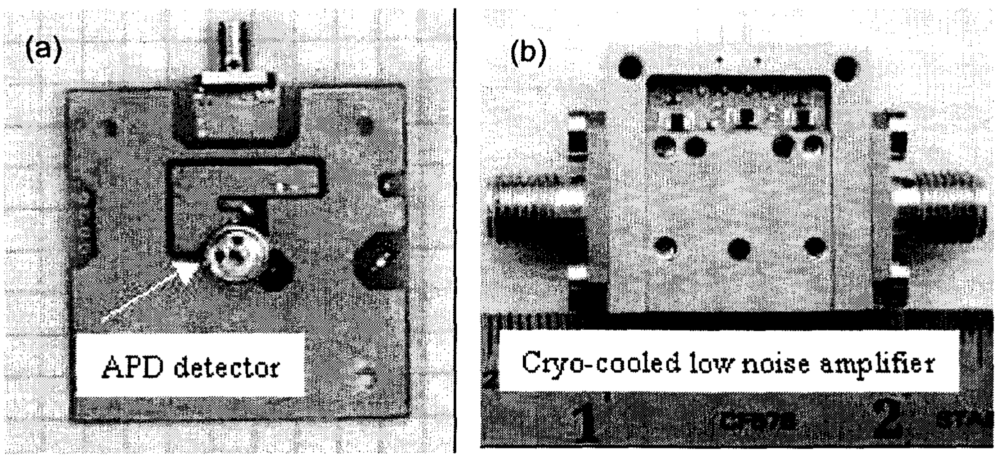

Figure 11 - Representative APD Detector and Low-Noise Amplifier Being Used to Develop Photon-Counting Receiver Front-End.

most important of these is that while telescopes are generally designed to image over a relatively large optical field of a few arc minutes, the field of an optical receiver is driven by the need to acquire the signal initially, and efficiently collect light which appears to be incident from off-axis because of atmospheric seeing. This easing of the receiver field requirement allows the optical designer to use a relatively fast (~F/1), spherical mirror. The low focal ratio has cost savings implications which ripple through the system design. For example, a low focal ratio allows for a shorter secondary mirror support, which can be less massive, which allows for reduced requirements on the axis bearings. The use of a spherical mirror has similar implications for the optical design; a segmented mirror can be used in which all of the segments are identical, drastically reducing fabrication costs, polishing costs and testing costs.

Furthermore, this 'interchangeable parts' approach provides for the on-site storage of a few spare segments, likewise reducing maintenance costs and improving receiver reliability and availability.

An example optical design capitalizing on these features is shown in Figure 12.

Here a 10-meter F/1 spherical segmented mirror is used to capture light from the distant transmitter. The large degree of spherical aberration evident from the ray caustic is easily corrected by the aspheric pair shown at prime focus. The result is a diffraction-limited spot over a 100 microradian field. This and similar designs have been analyzed for cost, and are expected to be a factor of 3-5 less costly than equivalent 10-meter astronomical telescope designs.

New Array of Small Telescopes ERT

One of the ideas currently being considered is to develop an Earth terminal based on the Lincoln Distributed Optical Receiver Architecture (LDORA). The architecture centers around an array of small telescopes paired with low-noise (thermo-electrically-cooled) photon counters. Performance is very nearly the same as with a single, high-performance telescope, both in the bright, turbulent atmosphere and in the vacuum channel. (Different detector design optimizations are used in these two extremes.) The modular nature allows for many options of cost reduction, and is directly scalable to much larger (or smaller) total apertures with only a linear growth in cost. Perhaps one of the biggest benefits is the fact that small telescopes can include sunshades that would allow operation to within a very few degrees of the sun, thus keeping availability very high.

A large receiver can be efficiently constructed using multiple small telescopes, each with its own detectors. A master 1 GHz (i.e., the slot rate) clock, slot-synchronized to

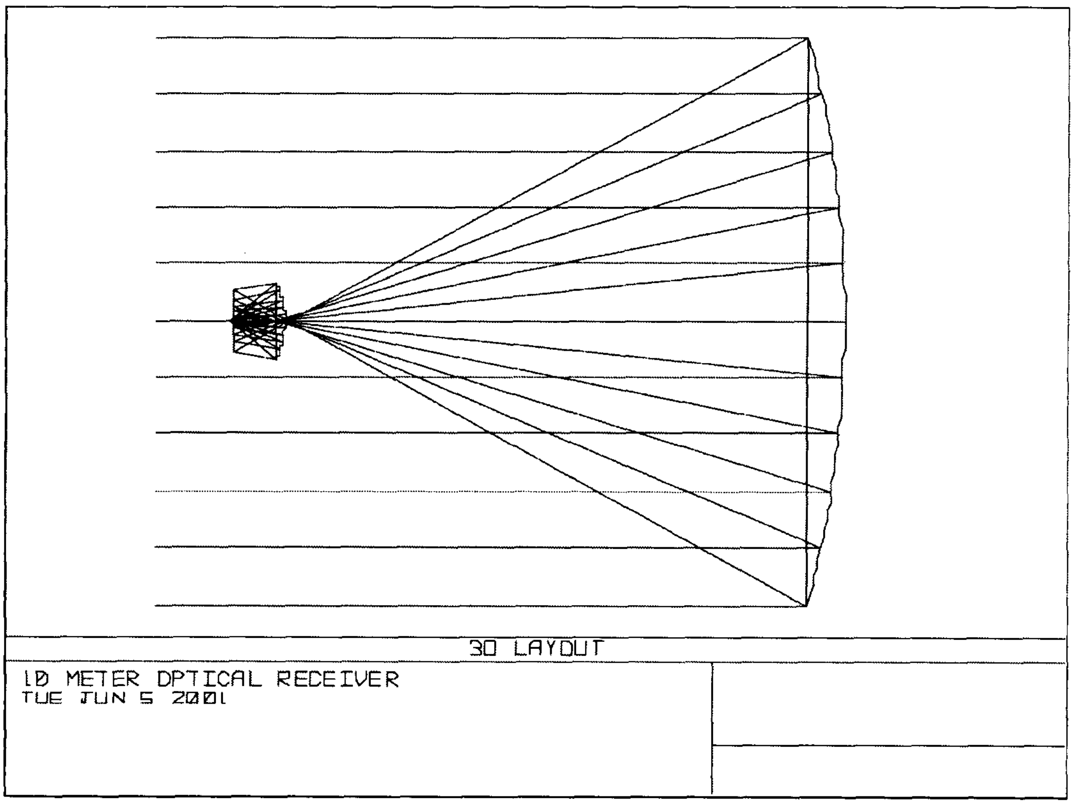

Figure 12 - Optical Receiver Design Using Spherical Segmented Mirror and Aspheric Correcting Pair.

the incoming stream, would be fed to the array. Each telescope is told its time offset as calculated throughout the day by a central processor, which also tells it where to point. Fine tracking can be done by each telescope by monitoring the detector array and fine pointing with the gimbal. All detections are sent via a 100 Mbps-class Ethernet star network to a fast switch which sends all the measurements to the decoding electronics.

Slot synch offsets are monitored via dithering techniques. PPM word and FEC codeword synch can be implemented in a number of ways including startup sequences, fixed deadtime patterns which add lines to the received spectrum (at the cost of increased peak power,) or by dedicating a small TDM subchannel to synch patterns. The receive array architecture is shown in Figure 13.

The array architecture scales very well to space-based systems. In either case, the selection of telescope size and number can be made to minimize cost while keeping performance the same. An extra 1 dB more receiver area costs, in general, 1 dB more in recurring dollars.

Sunshade--In order to maintain system performance while operating within 3° of the sun it is necessary to prevent the sun from illuminating the primary mirror. A sunshade that is 30 cm long with cells 1.5 cm wide and 10 cm high will meet this requirement. The use of an equatorial mount allows a relatively simple design consisting of flat panels. The panels are oriented perpendicular to the mount elevation axis and the 3° sun angle. The internal surfaces of the sunshade would be coated to achieve very low reflectivity.

The large sunshade cells allow simple fabrication. We will investigate the possibility of extruding the cells in a process similar to the fabrication of commercial heat sinks. This is possible because with 0.64 mm thick cells the sunshade only reduces the telescope collection area by approximately 0.3 dB.

When operating telescopes at night the outer optical element must be maintained at temperatures slightly above the dew point to prevent condensation. This will be done by adding low power heaters, approximately 15 W, to the sunshade.

Detectors for Arrays of Small Telescopes—One type of detector being considered for this application is an InGaAsP/InP Geiger-Mode APD, and it is a great match for the LDORA concept. Geiger-Mode (G-M) APDs can be thought of as photon-to-digital converters which produce a digital logic-compatible voltage transition in response to a single incident photon. In this way G-M APDs completely eliminate many of the traditional sources of noise (read-noise, amplification noise, etc) involved in photon detection with analog receivers. In the G-M APD focal planes proposed for an LDORA-based Earth terminal, each pixel is mated to a digital timing circuit that records the arrival time of the first photon from each laser pulse. Microlens arrays can be used to increase the optical fill factor for each APD pixel. The APD configuration is shown in Figure 14.

A Geiger-mode APD is biased beyond the impact-ionization avalanche breakdown voltage for the diode. The amount of bias beyond breakdown is called the over-bias. When the APD fires, a circuit element is used to drop the bias to less than breakdown voltage for some period of time ("dead" time or re-arm time), before overbias is reapplied. Although excess noise due to the presence of both conduction and valence-band multiplication in linear mode avalanche photodiodes limits their sensitivity, both electron and hole multiplication are essential for Geiger-mode breakdown in APDs. The primary metrics for G-M APD sensitivity are the photon detection efficiency and the dark count rate. Dark count rate is also sometimes specified as the probability of a dark count occurring in a single time bin (per ns, for example)[13].

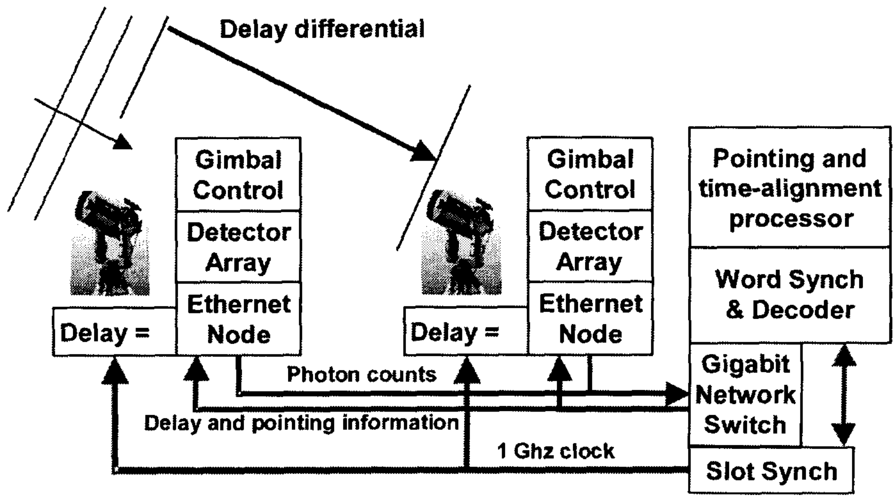

Figure 13 - Receive Array Architecture

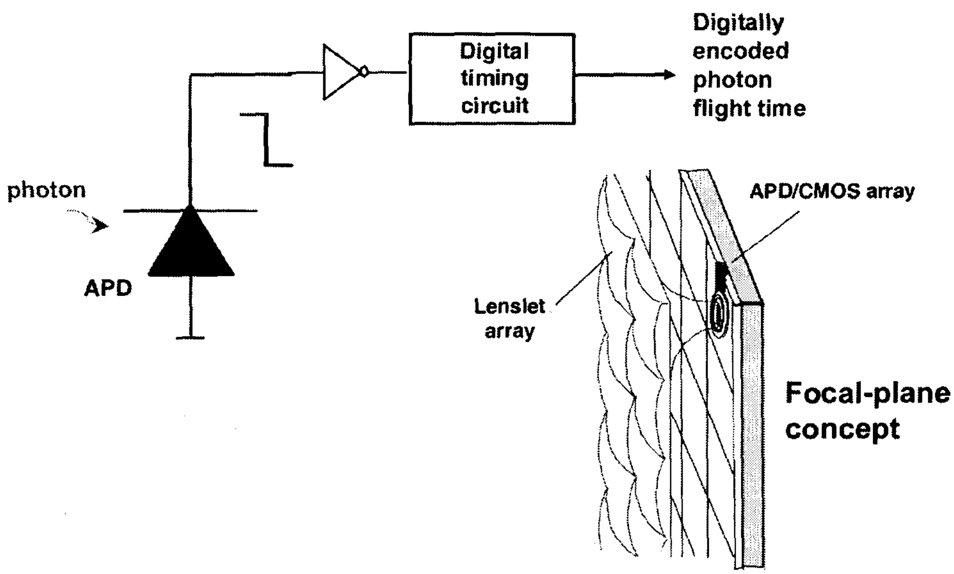

Figure 14 - Geiger-Mode APD Configuration

Earth Transmit Terminal (ETT)

The ETT must provide a signal for the FT to track and to deliver commands to the FT. Turbulence effects on the laser beam as it passes through the atmosphere causes wide variation in the received power at the FT. The chosen approach to solving this problem is to use multiple uplink beams. As with the ERTs, there are multiple approaches to generating the multiple beam signal.

The first two approaches use a single aperture but create multiple beams within it as shown in Figure 15. The uplink laser transmitter could be either a single laser source with the output optically split into several beams (as done for GOLD) or multiple lasers coupled through a beam combiner and transmitted through a single telescope aperture. An example of the latter was demonstrated in a ground demonstration where the beams from 4 lasers were imaged separately to form a ring of spots around the primary mirror but overlapping in the far-field.

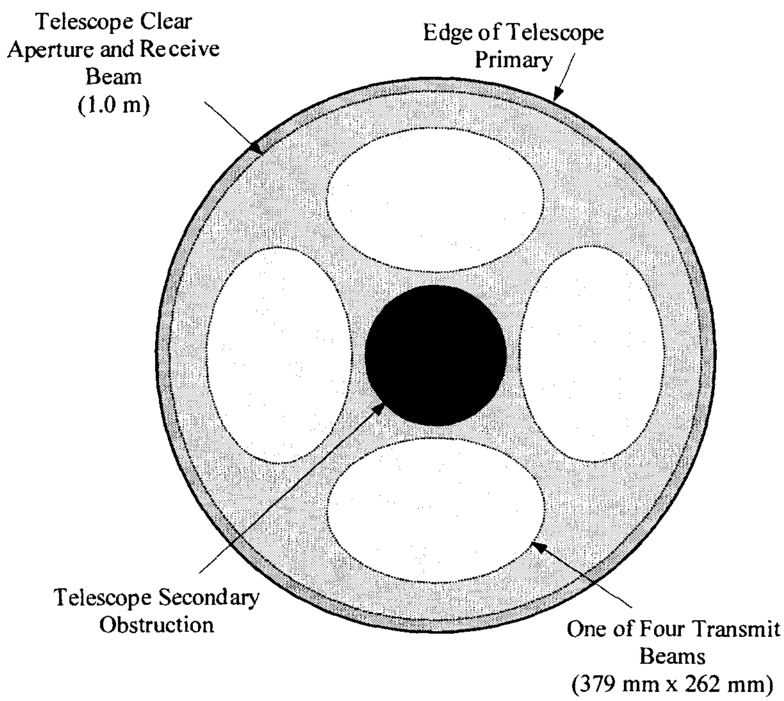

Figure 15 - Multiple Beams Formed On a Single Aperture

To facilitate commanding the flight terminal through the uplink channel, the laser should also be capable of being modulated at data rates of up to 1 kbps. The modulation format can be either direct amplitude modulation of the output power or a frequency selective pulse rate with a FSK data format.

Candidate laser sources include diode pumped solid state (DPSS) lasers based on a either a Nd:YAG (1064 nm) or Yb:YAG (1030 nm) gain medium, or fiber lasers based on Yb doped glass. DPSS lasers operate at a fixed wavelength while the fiber lasers can be tuned over a broad operating range, typically 1030 to 1100 nm. The flexibility in the fiber laser wavelength is achieved by using a master-oscillator power-amplifier (MOPA) geometry where the seed oscillator laser provides the wavelength control. DPSS lasers are much more mature at the multi-100 W power. generally possible at lower powers. A fiber based device has also demonstrated diffraction limited beam quality at the 300 W power level.

For uplinking data, both laser systems can be modulated at multi-kHz repetition rates. However, particular attention has to be given to the power stability and thermal issues when modulating such high power systems, and this will probably drive the final selection.

Another concept developed for implementing the beacons is to incorporate six, 30 cm aperture telescopes on a single equatorial mount. Optical power will be supplied by commercially available 20 W Ytterbium doped fiber amplifiers. Each telescope will use an amplifier for a total transmitted power of 120 W. The configuration of the beacon transmitter assembly is shown in Figure 16.

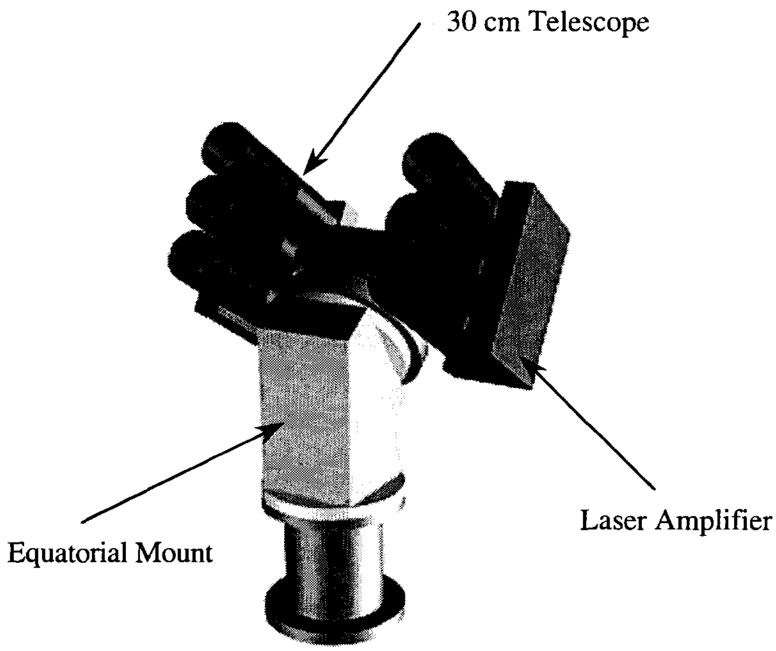

Figure 16 - Multiple Aperture Beacon Configuration

6. DEMONSTRATION OPERATIONS

The demonstration will last at least through one Earth year on orbit at Mars. Besides the increased data rates over today's RF systems, the demonstration will address operability issues such as predefined sequence operation, link set up and tear down, and weather mitigation techniques.

The mission operations for the MTO spacecraft and the lasercom demonstration are intimately intertwined as shown in Figure 17. The unique nature of the demo is that there is a path to and from MTO that is outside the usual Deep Space Network RF connection. Commands for the lasercom terminal can be sent via either the optical uplink or via the RF uplink. There are two paths for getting engineering data, again via optical or RF, and the terminal will be able to transmit "science" data. The Demonstration Operations Center (DOC) coordinates all lasercom activities and provides an interface to MTO operations.

The primary commanding mode for the lasercom terminal is via the DSN. For each lasercom pass, the desired operations (time to turn on/off, data source selection, data rate, etc.) will be predefined, sent from the DOC to MTO operations which will package them appropriately to send to the spacecraft via the DSN. Some "real-time" commanding via this link is desired to deal with weather and atmospheric

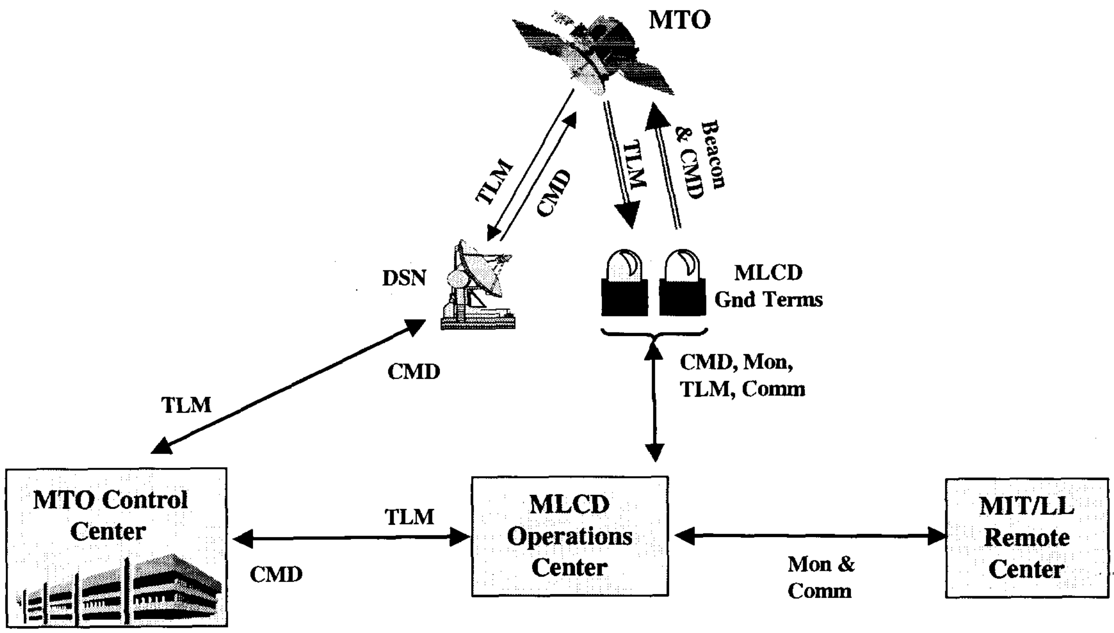

Figure 17 - MLCD Operations Diagram

conditions that may require changing, for example, the data rate. These commands, generated at the DOC, can change the internal configuration (data rate, etc.) of the lasercom terminal but will be firewalled so that no commands may be forwarded from the terminal to the spacecraft.

On the telemetry side there are again two paths, though for somewhat different reasons. Data (science or engineering telemetry) can be sent to Earth via the lasercom terminal. The selection of data, formatting, etc is done by the avionics and the lasercom accesses the appropriate space in storage to extract the data, add its own internal formatting and error-correction coding, and then transmit it to Earth. The data may be the same data that is being transmitted over the RF links, albeit potentially at different rates. It is possible that the lasercom terminal may add/multiplex additional engineering data into the data stream. The spacecraft monitors terminal parameters like power and includes those in engineering telemetry that is passed over the RF link. In addition to these, there are many 'test points" within the lasercom terminal that are available and that data can be requested and then sent via RF as part of the engineering telemetry. It is worth noting that, at least during the initial stages of the demonstration, a DSN pass must be scheduled to coincide with each optical pass to allow downlinking of the terminal engineering data.

Due to the vagaries of weather and atmospheric conditions, operations strategies for mitigation of these effects will be explored. One possibility would be to have multiple terminals within the same beam simultaneously receive the same data to guarantee a reasonably high percentage of the time getting through to at least one terminal. On the other hand, buffering and retransmission strategies can be used to downlink the data to single geographically (and hopefully meteorologically) diverse stations in a form of temporal diversity.

7. CONCLUSION

High-rate, low mission impact communications will revolutionize deep space science. Data rates that are 10 – 1000 times more capable than current RF systems will allow new kinds of connectivity and enable new kinds of scientific investigations. Except for the long inherent delays due to the vast distances involved, establishing a "virtual presence" will be possible, enabling both undreamed of planetary sensors and high-rate communications with future astronauts. The lasercom terminal to be flown on the Mars Telecom Orbiter by NASA in 2009 will be the first deep space demonstration of this revolutionary technology. The knowledge and experience gained will enable NASA to design, procure, and operate cost-effective future deep space optical communications systems.

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